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Ethanol–electric propulsion as a sustainable technological alternative for urban buses in Brazil

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Abstract

The option of fitting electric motors to vehicles that are more efficient and quieter than internal combustion engines has been hampered considerably, looking only at the use of conventional batteries supplying electricity. This is basically due to low gravimetric and volumetric energy densities of these devices that result in shorter autonomy, in addition to more weight and less usable space in the vehicle. An alternative that could make electric motors more attractive for vehicular applications by replacing batteries as the main electricity source is the fuel cell. Hydrogen is the main fuel used in these cells, but the hydrogen storage systems developed so far are heavier and bulkier than their equivalent for conventional liquid fuels such as diesel, gasoline and alcohol, despite heavier energy densities compared to batteries.

This paper reviews technological aspects of fuel cells, the main storage systems for hydrogen and other energy sources, data on fuel use and the types of vehicles most commonly used in the Brazilian road transportation sector, followed by an overview of the insertion of hybrid ethanol–electric buses in Brazil.

Keywords: Ethanol; Fuel cell; Electric vehicles; Hydrogen

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Contents

1. Introduction

Although somewhat hobbled by slumping oil prices in 1986, the quest for oil substitutes that began after two major crises (1973 and 1979) is currently being spurred by rising concern for the environment. Outstanding among these concerns are gases produced by human activities that step up the greenhouse effect, particularly CO_2 emissions caused by burning fossil fuels. However, in order to substitute fossil fuels on sustainable bases, it is not enough simply to seek alternatives among the primary renewable sources and energy vectors obtained from them, for storing and transporting energy in forms equivalent to those found today in the oil-based liquid energy vectors such as gasoline, diesel oil, etc. Good examples of the substitution efforts in Brazil are sugarcane and the ethanol distilled from it. However, in parallel to all these efforts, a major drive is becoming increasingly necessary in order to achieve higher levels of efficiency for the end-uses of energy. Within a timeframe that is difficult to estimate accurately, this task may be completed satisfactorily in the transportation sector through the use of electric vehicles driven by fuel cells.

Fuel cell studies focus mainly on the use of hydrogen as a reduction agent (fuel). Despite its advantages for use in fuel cells, including high reactivity and the formation of a simple end-product (steam), this substance offers several technical disadvantages, mainly in terms of storage, compared to other fuels that could also be used in these devices, such as methanol, ethanol, hydrazine, ammonia, etc. [1]. The first three offer the advantage of remaining liquid at room temperature (for easier fuel transportation and storage) while the latter (although a gas like hydrogen) can be stored more easily in pressure vessels [2].

For the fuel cell technological route that stipulates the use of alternative liquid fuel energy vectors that are easier to store, distribute, etc., methanol (CH_3OH) is the prevailing alternative in research projects carried out in the more developed countries. Several electric vehicle prototypes have already been produced by the main auto-assemblers, driven by fuel cells that run on hydrogen obtained by reforming methanol. However, ethanol (C_2H_5OH) may well be the best option among the alcohols, particularly for countries with better facilities for producing this energy vector, such as Brazil, which is already endowed with an ample production, storage, transportation and distribution infrastructure. The main raw material of Brazilian ethanol is sugarcane (renewable biomass), in contrast to methanol, whose most economically feasible production route all over the world is based on natural gas (fossil). Nevertheless, in the early days of its production, biomass was the raw material most commonly used to produce methanol, mainly timber. Another important aspect to be

taken into consideration from the environmental standpoint is the low toxicity of ethanol compared to the other fuels mentioned above, except for non-toxic hydrogen. This has direct repercussions on matters related to handling these fuels on a daily basis, as well as the severity of their impacts on the environment, in case of accidental leaks [3].

2. Context

Brazil's National Fuel Alcohol Program—PROÁLCOOL was launched in 1975, based on an initial strategy of substituting gasoline in the internal combustion engines of light vehicles, mainly Otto cycle. Phased in through blends initially at small percentages, it today reaches 24%, with no need for any technical modifications to vehicles. After the second oil crisis in 1979, Brazil took the initiative of producing vehicles driving on pure fuel alcohol. However, some alterations were required to these vehicles (engine, piping, fuel pump, fuel tank, etc.) that had not been required previously when alcohol was blended with gasoline, although maintaining the technological route established more than a hundred years earlier for vehicles driven by internal combustion engines. During the two oil crises mentioned previously, attempts at fuel substitution were aimed mainly at gasoline.

Today, with the advent of flex-fuel vehicles in Brazil, it is possible to drive Otto cycle engines on any percentage of gasoline $\times$ alcohol blends. However, the disadvantages of internal combustion engines remain compared to their electric counterparts, including high noise levels and the low energy efficiency of heat engines limited by the Carnot cycle. Another important item related to more rational energy use is the fact that even when internal combustion engines are fitted to hybrid vehicles, they must keep ticking over even in neutral gear with no useful output during constant traffic halts in modern cities [4]. Hybrid vehicles are driven by two or more energy conversion systems. The most common configuration currently works with a set of batteries and an internal combustion engine. Additionally, due to more flexible construction, electric engines can be linked directly to vehicle wheels, reducing losses through the transmission systems normally fitted to vehicles driven by internal combustion engines.

The main stumbling-block preventing electric motors from being used for automotive vehicle traction has always been their batteries [5]. The current trend towards fuel cells may well result in a breakaway from this technological paradigm through underpinning the feasibility of electric motors in the automotive sector. However, conventional batteries are still used advantageously in many prototype electric vehicles driven by fuel cells, although far fewer than electric vehicles, which use them exclusively for regenerative braking systems and responding to upsurges in power demands. This would result in hybrid vehicles similar to those running on batteries and explosion motors, although avoiding the use of the latter.

Other than markets for special vehicles such as stackers, mine operations, airports, small security and recreational vehicles (golf carts), transportation for people with special needs (electric wheel chairs), etc., the low gravimetric and volumetric energy densities of batteries curtails the use of space and the autonomy of vehicles for common use [6]. In order to deal with these problems, almost all of the world's automobile manufacturers are involved in research projects analyzing the use of fuel cells in electric vehicles [7]. At a time when several alternatives for electric vehicles driven by fuel cells are under discussion, the efforts of several different groups are already producing prototypes that could trigger a radical change in the technological paradigm, similar to the shift from steam-driven machines to

the explosion motor, which would ensure the feasibility of the advantages of electric traction in road vehicles.

3. Technical and economic data for different energy storage systems

The list of the higher calorific values (HCVs) of hydrogen and some commonly used fuels, shown in Table 1, highlights the marked difference between the hydrogen value compared to the others. In this aspect, hydrogen is far superior, having a HCV that is 2.88 times that of liquid petroleum gas (LPG), ranked second in this Table.

Nevertheless, the expectations for hydrogen are thwarted to some extent, when analyzing the devices required to store it, compared to those for other fuels. Fig. 1 presents

Table 1
Higher calorific values of hydrogen and other fuels

Fuel	HCV (MJ/t)
Hydrogen	141,840
Liquid petroleum gas (LPG)	49,163
Automotive gasoline	46,946
Diesel oil	44,979
Industrial fuel oil	42,197
Anhydride ethyl alcohol	29,665
Charcoal	28,424
Hydrated ethyl alcohol	27,824

Source: [8].

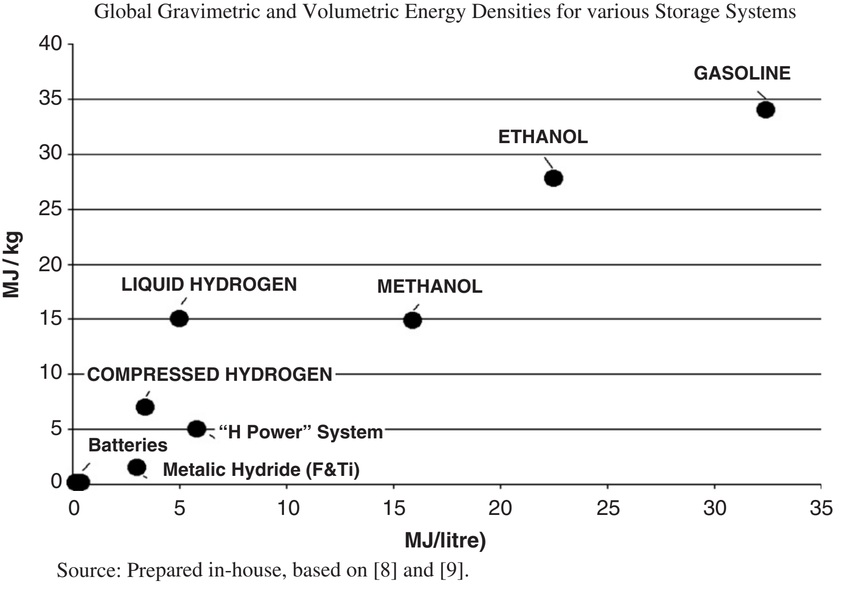


Fig. 1. Global gravimetric and volumetric energy densities for various storage systems. Source: Prepared in-house, based on Refs. [8], [9].

the global energy densities for some energy vectors, including the weights and volumes of their respective containment devices.

The data presented above shows that—despite the high energy density of hydrogen, with a HCV of 141,840 MJ/t—if the devices required for its storage are also taken into consideration, this fuel is at a marked disadvantage compared to its more conventional counterparts, in terms of its gravimetric and volumetric energy densities. Compared to the other systems presented, hydrogen outranks only batteries. Particularly noteworthy are the marked differences in these figures for hydrogen stored in cylinders compared to conventional liquid fuels such as gasoline, which is almost ten times superior in energy by volume (MJ/lt) and five times in energy by weight (MJ/kg). Although electric trolleybuses and buses do not have to deal with energy storage problems, they are powered through an electrified overhead network that requires an expensive poles and cables infrastructure that curtails the freedom of movement of these vehicles, with little flexibility for rearranging the lines [4].

Although hydrogen-powered vehicles may be feasibly able to attain autonomy greater than that of vehicles driven by electricity stored in batteries, hydrogen storage systems are still at a great disadvantage compared to vehicles fitted with internal combustion engines using conventional energy vectors. This means that hydrogen storage is one of the main challenges hampering its establishment as an alternative fuel, particularly for the automotive sector, which is extremely demanding in terms of weight and volume. Other disadvantages of hydrogen as an energy vector include: the need for heavy investments in its production infrastructure; large-scale storage, transportation and distribution facilities that do not yet exist for this fuel; and also the need to deal with the small-scale storage problems hampering its vehicular use that requires light, compact and low-cost systems that endow vehicles with good levels of autonomy.

An alternative that responds to the issues of hydrogen storage, of storage, distribution and transportation makes use of intermediate hydrogen vectors. These intermediate vectors are substances whose molecules contain hydrogen that can be released at the time and place of use, through specific techniques such as reform and partial oxidation. In addition to presenting different vehicle prototypes whose technological routes store hydrogen in pressure vessels or ultra-cooled as a liquid, the world's automobile industry has also developed ways of using methanol as an intermediate hydrogen vector for supplying the fuel cells. Good examples include the following prototypes: NECAR 3 and NECAR 5 produced by DaimlerChrysler, the Golf produced by Volkswagen, the Zafira produced by General Motors, TH!NK FC5, SUV P2000 and FOCUS produced by Ford, RAV 4 produced by Toyota, FCV produced by Nissan, etc.

Some research institutions have also become interested in studying the use of methanol by vehicles powered by fuel cells, including Georgetown University, where feasibility studies began in 1983 on electric buses powered by fuel cells. Two bus prototypes (Test-Bed Buses Model) were built in 1994 and 1995, with three other buses (UTC Bus and Ballard X1 Bus Models) in 1998 and 2001. All these bus prototypes were built at Georgetown University on the basis of the concept of on-board methanol reform [10], which might be called methanol–electric. In addition to methanol, ethanol may also be used as an intermediate hydrogen vector. This might well be the best alternative for Brazil because, as mentioned in the introduction to this paper, fuel alcohol is already well-equipped with a broad-ranging production, storage, transportation and distribution infrastructure that extends nationwide.

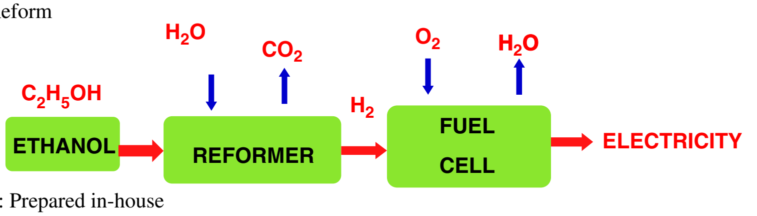
In Brazil, prototypes are also being developed for electric vehicles powered by fuel cells, undertaken by the academic sector through partnerships with government entities and, in some cases, with the participation of industry and international agencies. These vehicles are designed to run on hydrogen stored in cylinders as well as reformed ethanol: the VEGA II car developed through a partnership between Brazil's Ministry of Mines and Energy and the University of Campinas (MME and UNICAMP); some hydrogen bus projects in São Paulo through a partnership linking Brazil's Ministry of Mines and Energy with the Metropolitan Urban Transportation Enterprise, the United Nations Development Program and the Global Environment Facility (MME, EMTU, UNDP and GEF); as well as in Rio de Janeiro through a partnership linking the Graduate Engineering Program Coordination Unit (COPPE), the Institute of Technology for Development, Petrobras, Eletra and Caio. Also in Rio de Janeiro, the International Virtual Institute of Global Change (IVIG) at the Graduate Engineering Program Coordination Unit, Rio de Janeiro Federal University (COPPE/UFRJ) started to analyze the development of an electric bus driven by fuel cells in late 1999, focused on the concept of on-board ethanol reform, but was unable to obtain funding to continue this project.

4. Technological routes for using ethanol in fuel cells

Fuel cells are devices that convert the chemical energy in a fuel directly into electricity without passing through the heat cycle [1]. In physical terms, a fuel cell consists of two electrodes, the anode where the fuel is oxidized and the cathode where the oxygen is reduced, separated by ion-carrying electrolytes. The different types of fuel cells have been classified on the basis of the electrolytes used: acid cells such as the phosphoric acid fuel cell (PAFC); alkaline cells such as the alkaline fuel cell (AFC); solid polymer electrolyte cells such as the proton exchange fuel cell (PEM); the molten carbonate fuel cell (MCFC); and the solid oxide fuel Cell (SOFC). Hydrogen is the main fuel used in the cells, but other energy vectors may also be used in these devices, including alcohols such as methanol and ethanol, with the latter of special interest to Brazil, as already mentioned.

There are basically two ways of using ethanol in fuel cells, which may also be used for methanol, as well as ammonia and hydrazine. As shown in Fig. 2, the former is based on the reform concept where ethanol appears as an intermediate hydrogen vector or carrier that should be extracted previously for subsequent use in the fuel cells. In this case, the fuel cells are in fact fed with hydrogen containing small amounts of contaminants such as carbon monoxide (CO) and carbon dioxide (CO_2), which are by-products of the reform process. Carbon monoxide is a major problem for the catalysts commonly used in today's

Prior Reform



Source: Prepared in-house

Fig. 2. Prior reform. Source: Prepared in-house

proton exchange fuel cell (PEM) fuel cells that operate at low temperatures, as is the case with platinum [1]. The word "reform" is being used generically here. In addition to steam reform as such, there are other ways of obtaining hydrogen from alcohols and hydrocarbons, such as partial oxidation. The second option is presented in Fig. 3, where ethanol is oxidized directly in the fuel cell anode, with no need for prior reform. However, there are still some technical challenges to be dealt with in order to ensure the satisfactory functioning of this type of fuel cell, with better progress being achieved in the use of methanol rather than ethanol [11].

From the environmental standpoint, it is important to stress that for both these options—prior reform and direct oxidation of ethanol—the carbon dioxide produced in these devices and emitted into the atmosphere (which also occurs when ethanol is burned in conventional internal combustion engines) has a nil emissions balance due to the origin of this fuel, which is sugarcane in Brazil. As this involves renewable biomass, the carbon cycle based on burning fuel obtained from this source is completed by the photosynthesis process, with the uptake of CO_2 from the atmosphere during the plant growth phase [12].

5. Comparative analysis of main fuels and number of road vehicles in Brazil

The data presented in Table 2 shows that fuel consumption is heavily concentrated in the transportation sector, with diesel oil accounting for 81.05% and gasoline and alcohol at 100% of the total consumption of this sector, compared to energy end-consumption. As can be noticed in Table 2, almost all diesel oil used in Brazil is consumed in road transport. Electricity plays a minor role in the transportation sector, through a small contribution in

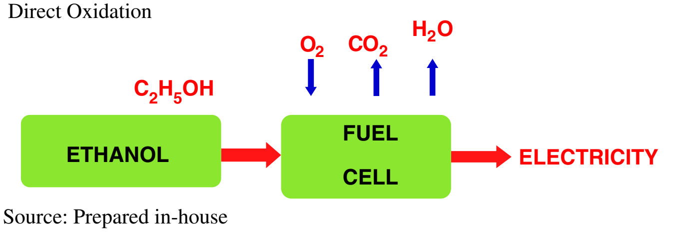


Fig. 3. Direct oxidation. Source: Prepared in-house.

Table 2
End-consumption profile of the main energy vectors in Brazil—2003

Sector	ENERGY VECTORS					
	Diesel (10^3 Tep)	Gasoline (10^3 Tep)	Alcohol (10^3 Tep)	Fuel oil (10^3 Tep)	Kerosene (10^3 Tep)	Electricity (10^3 Tep)
Energy end–consumption	30,812	12,396	5792	7225	2223	29,389
Total transportation	24,974	12,396	5792	699	2193	84
Road	24,263	12,354	5792	0	0	0
Rail	456	0	0	0	0	84
Water	255	0	0	699	0	0
Air	0	42	0	0	2193	0

Source: [8].

the rail sector. Although trolleybuses run in the city of São Paulo, their scale is not sufficient for inclusion in this table.

On the other hand, the data presented in Table 3 showing the number of vehicles in Brazil by fuel type indicates that diesel vehicles account for only 9.46% of the entire Brazilian fleet, while gasoline-powered vehicles reach 72.9%. This occurs despite the fact that the passenger km/liter efficiency of diesel buses is far higher than that of light vehicles powered by gasoline or alcohol, as shown in Table 4. This is due to the fact that vehicles for professional use—with heavier work demands—are fueled mainly by diesel oil in Brazil, while light vehicles drive mainly on gasoline and alcohol.

Drawn up on the basis of the data in Tables 2 and 3, Fig. 4 offers a comparison of the number of vehicles by fuel type and their respective consumption rates, showing a marked imbalance in terms of diesel oil.

6. Perspective for the insertion of ethanol–electric vehicles

The previous item shows that although totaling only 9.46% of the Brazilian fleet, diesel vehicles consume 97.15% of the total energy provided by road fuels in Brazil. To a certain extent, a scenario assigning high priority to substituting diesel-fueled vehicles would offer practical advantages in terms of logistics, through higher environmental and economic gains obtained through fewer vehicles. Moreover, due to the specific characteristics of their professional use in Brazil, diesel-fueled vehicles are clustered in fleets belonging to only a few owners, such as bus companies, school buses, etc. As these vehicles are larger and more robust, it is easier to equip them with devices that are not so compact and still in the development phase, such as reformers in fuel cells.

Conventional diesel-fueled urban buses could well be the starting-point for introducing sustainable technology, as they would offer immediate local and regional environmental

Table 3
Number of vehicles in Brazil by fuel type

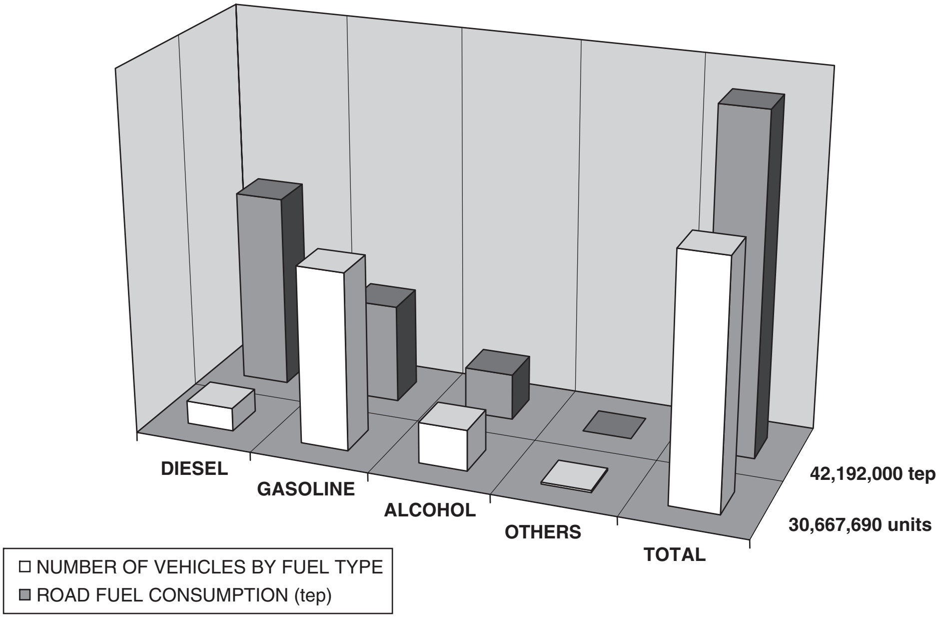
Fuel	Number of vehicles (%)	
Diesel	2,900,821	9.46
Gasoline	22,354,730	72.9
Alcohol	5,152,372	16.8
Others	259,767	0.85
Total	30,667,690	100

Source: Prepared in-house, based on Ref. [13].

Table 4
Specific consumption by passenger carried and ton transported

Vehicles	Passenger (km/l)
Light vehicles (alcohol or gasoline)	12.75
Buses (diesel)	148.5

Source: [14].



Source: Prepared in-house

Fig. 4. Fuel consumption and the respective road vehicle fleet. Source: prepared in-house.

gains to large towns and cities through reducing nitrogen oxide and particulate emissions, with less noise, etc., in parallel to global environmental gains through lower CO_2 emissions.

Based on the data in the previous items, an overview is presented for introducing ethanol–electric vehicles. As an alternative, a set of hybrid propulsion system configurations will be proposed, offering the possibility of steady improvements in energy efficiency as they become more sophisticated, with a more flexible timeframe for ensuring their feasibility.

6.1. Initial remarks on hybrid vehicles

In general, hybrid vehicles may be defined as those propelled by two or more energy conversion systems [5]. The most common hybrid vehicles are based on the conventional electric vehicle driven by batteries that operate jointly with an internal combustion engine. Other systems—ultra-capacitors and flywheels—are also used to operate jointly with the internal combustion engines in these vehicles. Basically, hybrid vehicles are based on configurations in series or in parallel. For the former, an internal combustion engine is connected to a power generator that feeds a group of batteries which supplies energy to an electric motor or set of electric motors that are connected directly to the wheels that in fact propel the vehicle. For the latter, the vehicle transmission system is fueled in parallel by an electric motor driven by a group of batteries and an internal combustion engine [5].

A hybrid vehicle offers the possibility of feeding back part of the kinetic energy for storage during the braking process. To do so, the status of the electric motor is reversed when braking, becoming a generator when part of the kinetic energy is converted once again into electricity for storage in the batteries. This system is known a regenerative braking. When used in hybrid configurations, internal combustion engines can operate on more stable bases that result in better sizing, as upsurges in power demands can be handled by the electric system. In actual fact, internal combustion engines in conventional vehicles are oversized in order to respond to heavy power demands when pulling away, overtaking, driving up slopes, etc.

Like generator groups, fuel cells may also be used in hybrid configurations, working jointly with a battery system or, as described in the previous paragraph, with ultra-capacitors and flywheels. In addition to the regenerative braking process, this also offers the advantage of more rational sizing, as the fuel cells can operate on more stable power systems in the vehicles. This means that hybrid configurations should also be taken into consideration, as hybrid vehicles fitted with Otto cycle internal combustion engines and their counterparts using ethanol fuel cells can operate equally well on more stable bases, with more rational sizing. In either of these cases, power demand surges will be met by the ancillary system: groups of batteries, ultra capacitors or flywheels.

6.2. *Ethanol–electric propulsors to be considered*

The configurations proposed for introducing this technology are subdivided into four types at rising levels of sophistication, in order to ensure a gradual uptrend in the learning curve. The series hybrid configuration is taken as the basis for preparing the simplified block diagram of ethanol–electric vehicles, presented in Fig. 5.

Based on the above remarks, and in order to estimate the effective global efficiencies of ethanol–electric propulsion, Table 5 presents some data on the efficiency ratings of the elements constituting the propulsion systems fitted to conventional vehicles driven by diesel motors and also the various hybrid electric systems fueled by ethanol described in Fig. 5. The conventional vehicle taken as the baseline is fitted with a diesel-powered internal combustion engine and a conventional mechanical transmission system.

Based on the data presented in Table 5, there are prospects for hybrid electric vehicles fitted with direct ethanol fuel cells achieving around twice the energy efficiency obtained through conventional diesel-powered vehicles. In addition to this significant contribution, the adoption of the final versions (Types 3 and 4) of the ethanol–electric vehicles in Brazil, particularly for urban buses, would cluster together the main advantages of these critical technology routes, compared to conventional systems using heat engines and fossil fuels or even alternative electric vehicles running on hydrogen:

Ethanol:

- Fuel that remains liquid at room temperature, easy to handle and store, no toxicity, renewable and widely accepted by the market,
- Environmental gains that are not just global, with lower greenhouse gases emissions (such as CO_2) but also immediate benefits at the local and regional levels through substituting diesel motors, reducing sulfur emissions (acid rain) as well as particulate emissions and noise pollution,

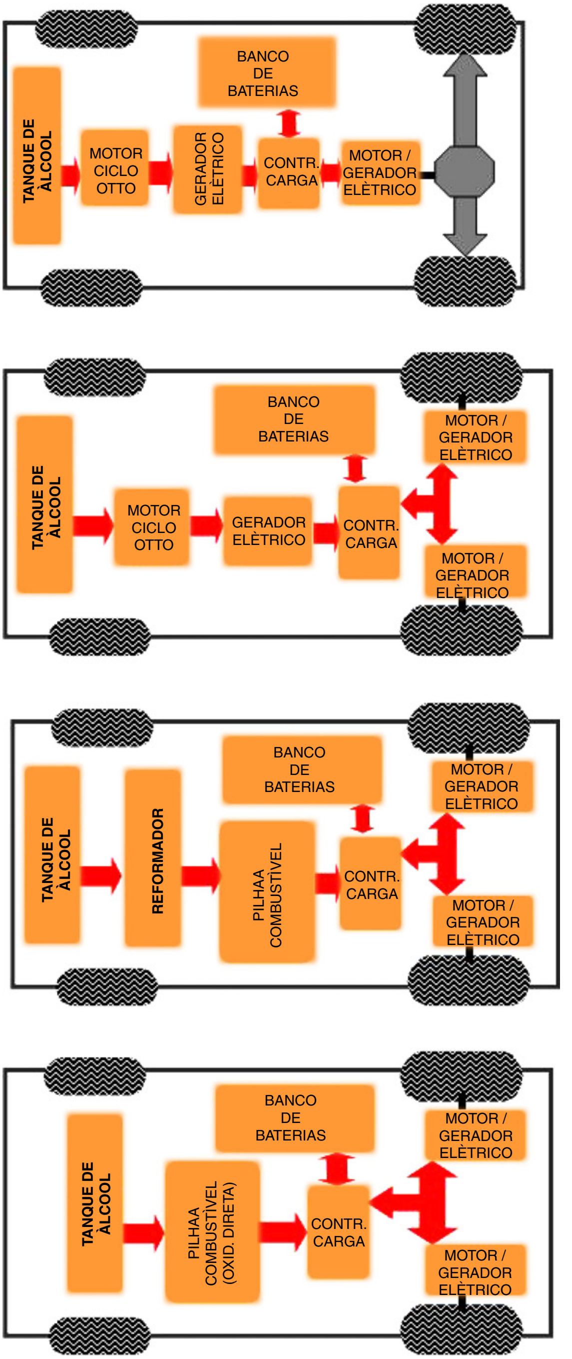


Fig. 5. Types of Ethanol–electric propulsors considered. Type 1: Ethanol–electric: hybrid—Motor Generator Group (Otto cycle) fueled by alcohol, group of batteries and electric motors connected to a conventional mechanical transmission system. Type 2: Ethanol–electric: hybrid—Motor Generator Group (Otto cycle) fueled by alcohol, group of batteries and electric motors connected directly to the wheels. Type 3: Ethanol–electric: hybrid—alcohol fuel cell (with reform), batteries and electric motors connected directly to the wheels. Type 4: Ethanol–electric: hybrid—alcohol fuel cell (direct oxidization), batteries and electric motors connected directly to the wheels.

Table 5
Estimated global efficiency ratings for the proposed configurations

Propulsion and fuel	Efficiency of the main components of the propulsion system *		Transmission efficiency *	Regenerative braking gain	Global efficiency	Cumulative advantages
Conventional diesel	30%		82,5%	(Not applicable)	24.75%	(Baseline)
Diesel–electric						
Diesel motor (30%)	Electric generator (97%)	Power electronics (95%)	82,5%	+ 30%	29.65	• Regenerative braking
Ethanol–electric—Type 1						
Otto cycle motor (20%)	Electric generator (97%)	Power electronics (95%)	82,5%	+ 30%	19.77	• Regenerative braking • Less noise • Renewable fuel
Ethanol–electric—Type 2						
Otto cycle motor (20%)	Electric generator (97%)	Power electronics (95%)	Electric motor (97%; connected directly to the wheels)	+ 30%	23.24%	• Regenerative braking • Less noise • Renewable fuel • Transmission efficiency
Ethanol–electric—Type 3						
Reformer ** (75%)	Fuel cell (H2;50%)	Power electronics (95%)		+ 30%	44.92%	• Regenerative braking

Table 5 (*continued*)

Propulsion and fuel	Efficiency of the main components of the propulsion system *	Transmission efficiency *	Regenerative braking gain	Global efficiency	Cumulative advantages
		Electric motor (97%; connected directly to the wheels)			• Renewable fuel • Transmission efficiency • Cell efficiency (H2)
Ethanol–electric—Type 4 Direct oxidation ethanol fuel cell (40%)	Power electronics (95%)	Electric motor 97%(Connected directly to the wheels)	+ 30%	44.92%	• Regenerative braking • Less noise • Renewable fuel • Transmission efficiency • Reformer not required • Cell efficiency (ethanol)

Source: [5,7,11,15–18]

*Absolute values were presented, or the average values were calculated for the ranges presented through the references.

**Estimated value based on the ethanol and diesel data.

- Makes good use of the ethanol production and distribution infrastructure, already fully mastered and easily available in Brazil.

Fuel cell:

- Gains in efficiency,
- Fewer moving parts and lower operating and maintenance costs.

Hybrid system:

- More rational sizing,
- Allows a more gradual uptrend in the fuel cell learning curve in order to obtain gains of scale and better economic feasibility for fitting to other types of vehicles in future.

Electric motor:

- Quieter and more efficient propulsor,
- Easier to install the regenerative braking system,
- More efficient transmission through the possibility of direct connection to the wheels,
- Fewer moving parts and lower operating/maintenance costs.

Challenges of the proposed technological route:

- The prototypes produced by the main research groups all over the world using alcohol in the fuel cells opted for methanol rather than ethanol, with the on-board reform route prevailing,
- Despite the energy efficiency of the fuel cells compared to the heat engines, lower noise and emission levels, the economic competitiveness of fuel cells still constitutes a barrier to their implementation. This is due largely to the absence of production-line output of this device with the resulting gains in scale, which could build up over the medium and long terms.

In closing, Fig. 6 presents an analytical map showing the paths for introducing the hybrid propulsion alternatives over time, including some possible forks. The options are defined on the basis of the technological scenarios described in the previous item over three time frames: short (zero to 5 years); medium (5–10 years); and long (more than 10 years).

7. Conclusion

Over the past few decades, massive efforts have been channeled towards substituting fossil fuels in Brazil. In the transportation sector, they were guided mainly by supply side logic through steadily increasing ethanol production intended to fuel conventional light vehicles fitted with internal combustion engines. On the other hand, as increasingly large tracts of arable land will be required to step up the production of ethanol for fueling a steadily expanding fleet of vehicles, in parallel to rising demands for exports of this energy vector to other countries interested in renewable fuels, efforts are also required to replace fossil fuels, guided by demand-side logic. This may be achieved through more efficient

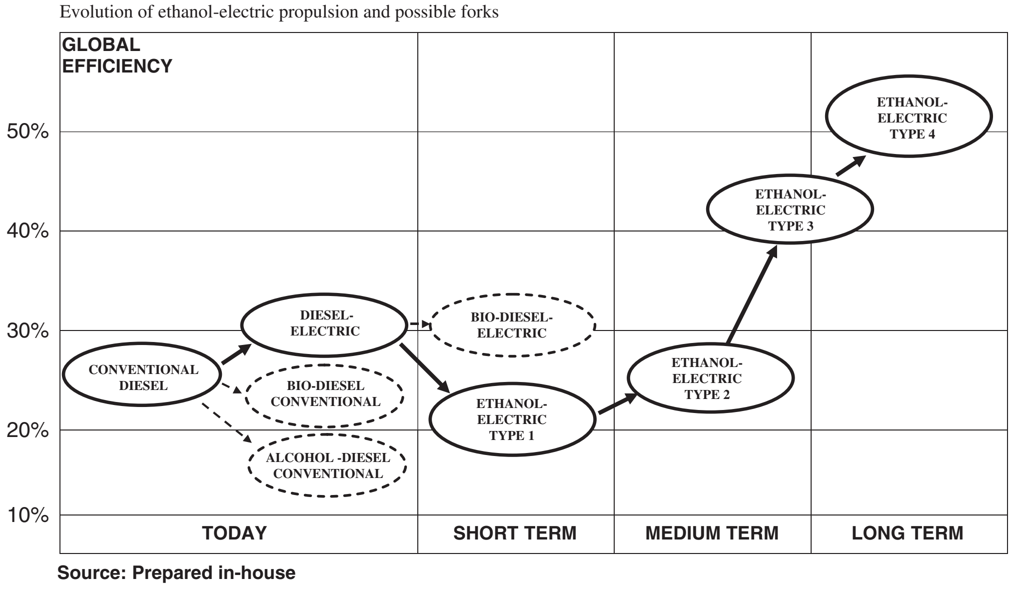


Fig. 6. Evolution of ethanol–electric propulsion and possible forks. Source: prepared in-house.

energy end-uses. In terms of the transportation sector, and depending on the outcome of the research and development projects under way all over the world, a leading role may be played by propulsion systems powered by fuel cells and electric motors.

As shown in this paper, a comparison of transportation operations and energy consumption data in Brazil highlights this characteristic: only a small portion of the Brazilian vehicle fleet accounts for most of its fuel consumption as diesel oil. Consequently, in a possible substitution scenario, this offers a logistical advantage as greater environmental and economic gains would be achieved through a smaller number of vehicles, through assigning top priority to substituting conventional diesel vehicles by others running on renewable fuels with more energy-efficient systems, such as fuel cells.

As ethanol is a renewable liquid energy vector produced in large quantities and with a nationwide distribution network, the progress of research projects analyzing ethanol end-use in fuel cells through either the reform route or direct oxidation may respond to key issues related to efficient and environmentally sustainable energy uses, particularly in Brazil. These issues are related to the substitution of fossil fuels and the replacement of conventional vehicles by their electric counterparts. The latter have always faced massive technological barriers consisting of satisfactory energy storage solutions in batteries, or storage facilities for the hydrogen used by the fuel cells.

Should a substitution program be launched, installing ethanol–electric motors on urban buses to replace vehicles powered by conventional diesel cycle internal combustion engines, would produce immediate environmental gains at the local level: lower emissions of sulfur oxide and particulates, with less noise, compared to that produced by traditional buses in large towns and cities. Due to their specific usage characteristics, another important aspect that must be taken into consideration from a technological standpoint is the fact that diesel vehicles in Brazil are larger and more robust, like urban buses. This makes it easier to

install devices and upgrade their technology while still not fully compacted, for either ethanol reform or the fuel cells themselves.

Phasing in technologies for ethanol-electric and hybrid vehicles fueled by ethanol—as presented in this paper (Type 1 → Type 2 → Type 3 → Type 4)—would result in a gradual uptrend in the learning curve that is more feasible in economic terms. This situation indicates the potential application for hybrid propulsion technology as a way of (1) enhancing fuel use efficiency for transportation purposes and (2) substituting an oil product by a biofuel, as ethanol would replace diesel oil, while migrating to a more efficient propulsion system.

As a continuation of this paper, it would be interesting to draw up economic feasibility studies that include and quantify the environmental gains achieved through the substitution stages suggested here. This might well recommend that private enterprise and government entities should adopt this new technology for future "Green Fleets", as the best way of ensuring the economic absorption of these environmental gains through applying for tax incentives and obtaining carbon credits through clean development mechanism (CDM) projects. This approach would work towards ensuring the feasibility and possible introduction of ethanol-electric buses that would replace today's environmentally aggressive conventional diesel technology used in buses that are the main mode of urban transportation in Brazil, ushering in an alternative that is more friendly to mankind and the environment.

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